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Contribution of archaeological data to studies of earthquake history in the Iranian Plateau

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Abstract

We use archaeological evidence to identify ancient earthquakes in the vicinity of large 20th century events in the Iranian Plateau. Two large earthquakes on the Zagros Main Recent Fault were preceded by historical earthquakes in AD 1008 and AD 1107 and by earthquakes in the intervals AD 224–459 and 1650–1600 BC, giving return times of 1800–2100, 500–800, and 850–950 years. The AD 1962 (M_s 7.2) Bo'in Zahra earthquake on the Ipak fault in north-central Iran was preceded by an earthquake in 2000–1500 BC recorded at the Sagzabad mound, a return time of 3500–4000 years if there are no missing events. The AD 1990 (M_s 7.3) Rudbar–Tarom earthquake in the western Alborz Mountains was preceded by an earthquake in 1000–800 BC recorded at the Marlik mound, a return time of 2800–3000 years. The AD 1948 (M_s 7.2) Kopeh Dagh earthquake that destroyed Ashkabad, capital of Turkmenistan, was preceded by an earthquake in 10 BC–AD 10 recorded at Mithradatkert (Nesa) mound and by an earthquake in 2000 BC recorded at Ak Tapeh mound. Assuming no missing earthquakes, this region has an earthquake return time of about 2000 years. In Khorasan province, which was struck by a sequence of large earthquakes from AD 1936 to 1997, a mosque at Qa'en was destroyed in the mid-11th century AD, probably the historical earthquake of AD1066. In the absence of palaeoseismic investigations, archaeology offers the promise of recording earthquakes through more than one seismic cycle in different regions of Iran.

1. Introduction

The Iranian Plateau is bounded on the north by the Alborz and Kopeh Dagh deformed zones adjacent to the Turan Platform, and on the south by the Zagros fold-thrust belt and Makran accretionary wedge adjacent to the Arabian platform (inset, Fig. 1). Convergence between the Eurasian and Arabian plates, about 35 mm/year NE–SW (De Mets et al., 1990; Jackson et al., 1995), is accommodated across the Iranian Plateau and adjacent deformed zones, a region about 1000 km across, but this deformation, as defined by seismicity, tectonic geomorphology, and geology, is not uniformly distributed. Despite the contrast between the marginal fold belts and rigid tectonic blocks of the Plateau, the maximum principal shortening strain direction is consistently parallel to the direction of relative plate motion (Jackson and McKenzie, 1984; Gillard and Wyss, 1995).

The seismically active faults in Iran consist of: (i) numerous relatively short reverse faults distributed through the active fold-thrust border zones, and (ii) long strike-slip faults and subordinate reverse faults confined to narrow zones within the Iranian Plateau. The geology and palaeoseismology of active faults in Iran have not been studied to the degree that they have in industrialized countries. However, Iran has an advantage lacking in most regions: an abundant and diverse prehistoric archaeological record and a long period during which written historical records were kept (Ambraseys and Melville, 1982; Berberian, 1995a). These may be combined with geological, morphological, and seismological evidence to correlate many historical earthquakes with their source faults (Berberian and Yeats, 1999).

The seismic cycle of a fault, a critical issue in probabilistic models of seismic hazard analysis, needs to be learned on the basis of repeated earthquakes on the same fault. There are no known written records of historical earthquakes in Iran before the mid-8th century AD. Due to lack of palaeoseismological trench excavations, archaeological data must be used for insight into the long-term earthquake history of Iran. Here we use archaeological information for the period for which no written records have survived. The data are based on existing archaeological reports, most of which are not accompanied by radiometric dating. Another limitation is that, for a specific earthquake, the size of the destroyed area is poorly known. It is also very

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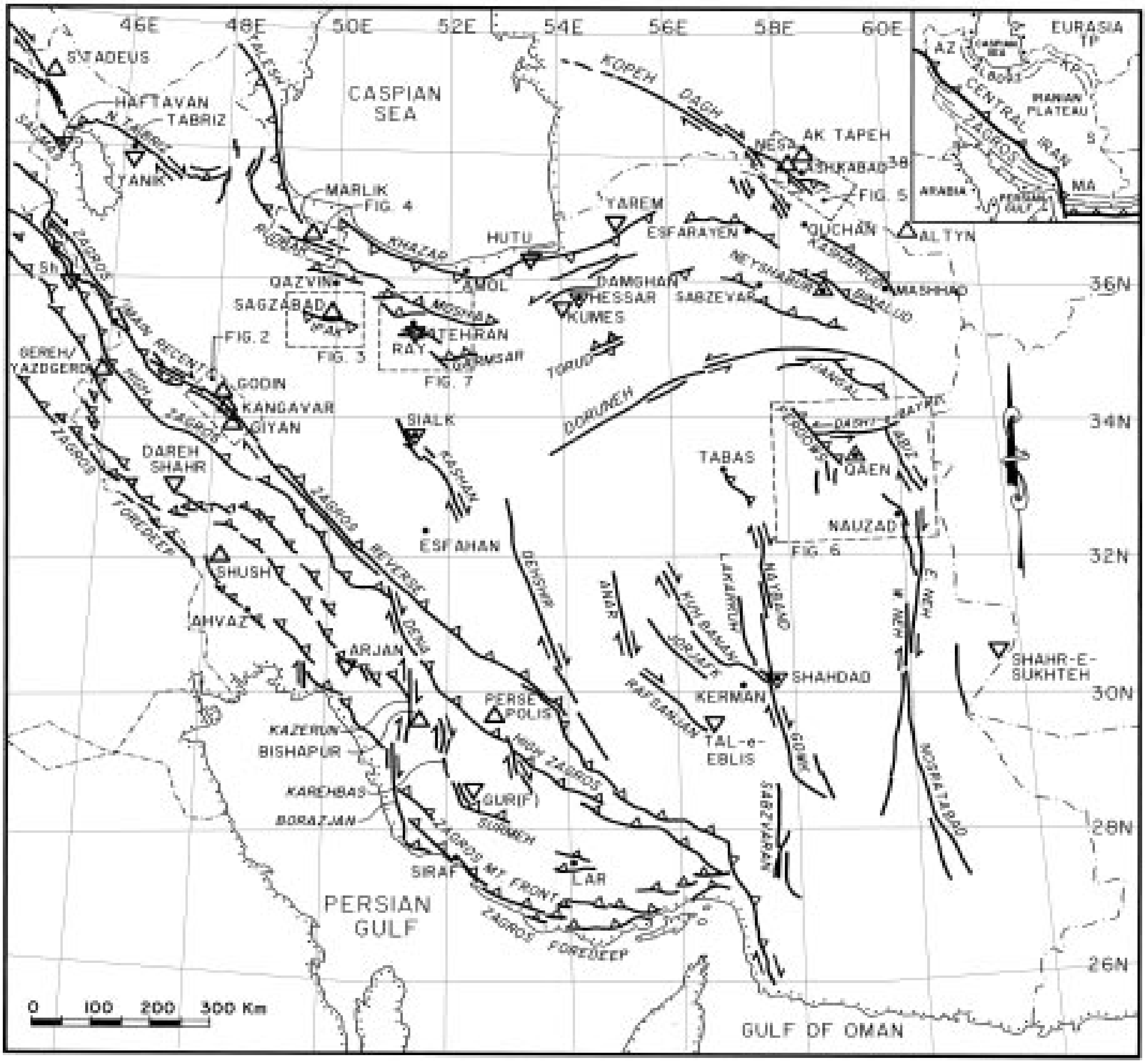

Fig. 1. Principal active faults (names in italics) and adjacent archaeological sites in Iran (modified after Berberian, 1976, 1977, 1981, 1995a,b, 1997; Berberian and Yeats, 1999; Berberian et al., 1999). Reverse faults shown with teeth on hanging wall side. Strike-slip faults shown with arrows. Faults without teeth or arrows: sense of slip unknown. Inset top right: map of Iran showing boundary with Arabian plate (line with teeth). AZ = Azarbaijan; KP = Kopeh Dagh mountain belt; MA = Makran accretionary wedge; S = Sistan; TP = Turan Platform. Archaeological sites that have provided earthquake information are shown by triangles. Those located near seismogenic faults or within the meizoseismal regions of large-magnitude earthquakes, but have not yet provided earthquake information in archaeological reports, are shown by inverted triangles.

difficult to prove that an archaeological site was continuously occupied during the period between damaging earthquakes. We compensate for this uncertainty by estimating a maximum time interval between large-magnitude earthquakes, because intervening earthquakes may be unrecorded due to the lack of a stratigraphic record. Unfortunately, archaeological literature for Iran rarely considers the possibility of natural disasters affecting structures or sites located in the vicinity of active faults and folds.

In some cases, archaeological evidence of strong ground motion is sufficient to suggest a specific source fault. In most cases, strong shaking could be attributed to more than one candidate fault or to a blind thrust. In such cases, following Reiter (1990), we consider the recurrence interval of an area source (earthquakes generated by any fault, known or unknown, within a defined region) rather than a line source (earthquakes generated on a specific fault or segment of a fault).

Fig. 1 locates archaeological sites with evidence of earthquakes and other archaeological sites close to seismogenic faults or to meizoseismal zones of historical large-magnitude earthquakes (cf. Berberian, 1995a). Here we combine tectonic and seismic data, archaeological reports, and results of fieldwork after large-magnitude earthquakes to document the maximum return times of several 20th century earthquakes. We present four examples of archaeological evidence for possible strong earthquakes within the meizoseismal zones of large- to moderate-magnitude earthquakes in the last half of the 20th century, allowing a maximum recurrence interval to be determined. We then discuss briefly other sites where the evidence for earthquakes is equivocal. These equivocal examples, supplemented by tables and figures summarizing archaeological and historical seismic data, are included as a guide to future archaeoseismic and palaeoseismological trench studies.

We use the equivalent M_s magnitudes of the historic (pre-AD 1900) and prehistoric events, following Kondorskaya and Shebalin (1977), Kondorskaya and Shebalin (1982), and Ambraseys and Melville (1982). Wherever possible, figures show the isoseismal lines of 20th century AD earthquakes to illustrate the damage distribution, which may contain possible information about rupture characteristics. However, for pre-20th century earthquakes or for large areas such as those in Figs. 6 and 7, ellipses covering the damaged zones are shown.

Care must be taken in distinguishing earthquake causes of damage and destruction of structures or for sudden abandonment of sites from non-earthquake origins such as invasion, revolution, climate change, or fire. A site may have experienced earthquakes during a cultural gap, but the absence of cultural horizons or continuous sedimentation may have prevented those earthquakes from being recorded. Too few sites have provided evidence for damage from the same earthquake, preventing the drawing of meizoseismal areas and the estimation of moment magnitude. Another problem is that many archaeological reports do not consider earthquakes in establishing why a site was abandoned or destroyed. However, archaeological paleoseismology has great potential in Iran, with its long human history and prehistory, and more than 250,000 archaeological sites.

2. The Zagros Main Recent Fault in the Dinevar–Nahavand Region

The Zagros Main Recent Fault (ZMRF) (Tchalenko and Braud, 1974; Berberian, 1995b) is an active right-lateral strike-slip fault >640 km long, which more or less follows the Main Zagros reverse fault separating the Central Iranian range-and-basin province to the northeast from the Zagros fold-and-thrust belt to the southwest (Figs. 1 and 2).

In the Dinevar–Nahavand region (Fig. 2), the ZMRF sustained surface rupture in two 20th century AD earthquakes: the Farsinaj earthquake in 1957.12.13 (M_s 6.7) and the Firuzabad earthquake of 1958.08.16 (M_s 6.6). The 1957 earthquake was accompanied by surface rupture on the Sahneh and Dinevar strands, and the 1958 earthquake resulted in surface rupture on the Nahavand strand and a portion of the Garrin strand of the ZMRF. A section of the Garrin strand may have ruptured during two foreshocks of M_s 5.7 and 5.5 (Ambraseys et al., 1973; Ambraseys and Moinfar, 1974a; Tchalenko and Braud, 1974; Berberian, 1995b) (Fig. 2). The Godin and Kangavar archaeological sites, which have earthquake information, lie within the $I_o = VII$ (MMI) isoseismal line of the 1957 earthquake, and those sites and the Giyan site lie within the $I_o = VII$ (MMI) isoseismal line of the 1958 earthquake (Fig. 2).

2.1. The c. 1650–1600 BC event at Godin mound

The Godin mound (Young, 1966, 1968, 1969, 1975a,b; Young and Levine, 1974; Young and Weiss, 1974; Henrickson, 1984) and Giyan mound (Herzfeld, 1929, 1933; Contenau and Ghirshman, 1935; Goff, 1966, 1971, 1980), 38 km apart, are close to the ZMRF (Fig. 2). The Godin site was abandoned after the 'Godin III:2' horizon (~1850–1650 BC) and before the 'Godin post-III:2 Graves' horizon (~1600–1400 BC) (Table 1). The Giyan site was abandoned between the 'Giyan III.IVC' and 'Giyan IIa-b' horizons (Table 1 and Fig. 2). The date of abandonment of both sites is constrained ~1650–1600 BC, based on ceramics that are dated by cultural correlation (Henrickson, 1986; T. Cuyler Young, personal communications, 20 July and 14 October 1998).

The Godin mound, between the Nahavand and Sahneh strands of the ZMRF (Fig. 2), was the site of a culture as old as 5500 BC. The Godin settlement, with extensive fortifications and important residential buildings with stone-paved floors and courtyards, was suddenly destroyed c. 1650–1600 BC. Many pots were smashed, a skeleton of a man was found crushed by falling roof debris, and large blocks of walls had fallen down. In places, the walls were preserved only to a height of almost 2 m (to the level of windows). All the reported evidence suggests that the sudden destruction was caused by a large-magnitude earthquake (Young, 1968, 1969; Young and Levine, 1974). The abundance of graves and the apparent lack of later settlements suggest that important socio-economic changes occurred following (and possibly as a result of) the postulated c. 1650–1600 BC earthquake. The Giyan site, excavated in AD 1931–1932, was abandoned at the same time, possibly the result of the same earthquake, even though there is no recorded evidence from the 1930s reports that the abandonment of Giyan is earthquake related.

2.2. The c. 224–459 event at the Kangavar Anahita Temple

The Anahita Temple of Kangavar from the Achaemenid period (550–334 BC) is located within the $I_o = VII$ (MMI) isoseismal of both the AD 1957 (M_s 6.7) and AD 1958 (M_s 6.6) earthquakes, and is close to the northwestern tip of the Nahavand fault strand of the ZMRF (Fig. 2). Archaeological excavation revealed displacement of large stone columns and huge blocks of stone walls, fallen columns and walls, and fractured dressed stones that littered the ground (Kambakhsh-Fard, 1994). Parthian clay-made coffins (250 BC–AD 224), buried at the foot of the eastern wall in the Parthian cemetery of the Anahita Temple, were broken and caved in (see plate VIIb in Kambakhsh-Fard, 1973, and figs.

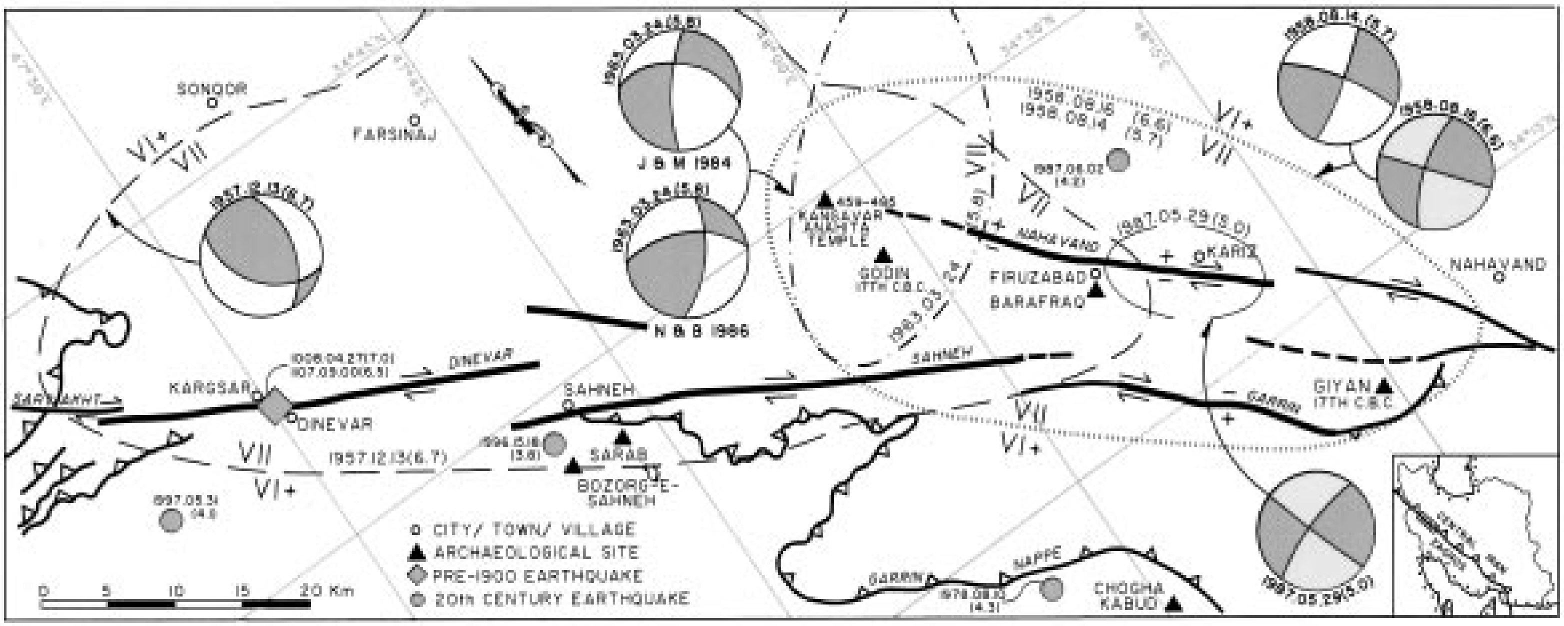

Fig. 2. Fault map (located in Fig. 1) of the central section of the Zagros Main Recent Fault with major archaeological sites (filled triangles). Meizoseismal areas of the 20th century AD earthquakes (MMI isoseismals marked with intensity) and macroseismic epicenters (filled diamonds) of the pre-20th century AD historical earthquakes, together with the date of each event and its estimated M_s magnitude, are also shown. Isoseismals (MMI) for the 1957, the 1958, and the 1963 earthquakes were taken from Ambraseys et al. (1973) and Ambraseys and Moinfar (1974a,b). The apparent NE–SW elongation of the 1963 isoseismal (Ambraseys and Moinfar, 1974a) may not necessarily infer a direction of faulting. It seems that for this moderate-magnitude earthquake the damage is influenced by the NE–SW trend of the Qarachay River valley. The 1957 (the Sahneh and Dinevar strands of the ZMRF) and the 1958 (the Nahavand and Garrin strands) earthquake ruptures are shown by thicker lines. Faults based on Berberian (1995b). The 1957 and 1958 focal mechanisms are from Shirokova (1962); the 1963 solutions are from Ni and Barazangi (1986) (N + B86 with waveform modeling indicating a depth of 8 km) and Jackson and McKenzie (1984) (J + M84); 1987 is the CMT solution from Harvard. Because of differences in first motions and S-wave polarization of the 1963 fault plane solutions, both mechanisms of N + B86 and J + M84 are presented. The early fault plane solutions were based on the published short-period polarities, and it is not possible to assess the reliability of these early solutions. Fault symbols are as in Fig. 1.

Table 1
Summary of archaeological and earthquake information of the Godin, Giyan, Kangavar, and Dinevar archaeological sites adjacent to the Zagros Main Recent Fault in the Dinevar–Nahavand region (see Fig. 2)

Approximate date	Godin	Giyan	Kangavar	Dinevar	Earthquakes (and faults)	Cultural event
1963	VII at Godin		VII at Kangavar	IV at Dinevar	**1963.03.24 (5.8)**	22 villages destroyed
1958				VII at Dinevar	**1958.09.21 (5.2)**	5 villages destroyed and 16 killed near Dinevar
1958	VII at Godin	VI at Giyan	VII at Kangavar	VI at Dinevar	**1958.08.16 (6.6), 1958.08.14 (5.7)** (Nahavand and Garrin)	Firuzabad + 170 villages destroyed
1957	VII at Godin	VI at Giyan	VII at Kangavar	VII + at Dinevar	**1957.12.13 (6.7)** (Sahneh and Dinevar?)	Farsinaj, Kangavar + 211 villages destroyed, 1130 killed
1384				Dinevar destroyed		Invasion of Timur
1218–1256						Invasion of Mongols
1107			**Water springs dried up toward end of Seljuk dynasty, possibly due to the 1107 earthquake**	VIII + at Dinevar	1107.09.00 (6.5)	**Kargsar–Dinevar region destroyed, large number of people perished**
1008				**IX at Dinevar**	**1008.04.27 (7.0)**	**Dinevar destroyed, 16,000 killed**
c. 636–642			Destruction and fire; 200 years gap			Early Islamic invasion
Before 640				Ancient Dinevar was built on an earlier town		
224–549 AD			**Major mid-Sassanian (459–485) reconstruction: fire and destruction (c. 250)**		**224–459 AD Kangavar earthquake**	
336–330 BC			**GAP**			Invasion of Alexander-III of Macedonia
c. 550 BC			Construction of Anahita Temple			
c. 1400–550 BC	Godin III-1 to II					
c. 1300–1000 BC	Iron I					
c. 1400–1300 BC	Godin III:1					
c. 1600–1400 BC	Post III:2 Graves	IIa-b				
c. 1650–1600 BC	**Complete destruction of Godin**	**< Gap >**			**Godin Earthquake (c. 1650–1600 BC)**	**Complete destruction of Godin and Giyan**
c. 1850–1650 BC	Godin III:2	III.IVC				
c. 1900–1850 BC	< Gap >	< Gap >				
c. 2100–1900 BC	Godin III:4	IVA				
c. 2200–2100 BC	< Gap >	< Gap >				
c. 2400-2200 BC	Godin III:5					
c. 2600-2400 BC	Godin III:6	< Gap >				
	< Gap >	Marked erosion surface				Partial abandonment at the end of Godin IV occupation
c. 4100–2600 BC	Godin X to IV	Giyan VC1 to IV				
c. 5500-4100 BC	Shahnabad (Seh Gabi)	Giyan VB (4500–3900 BC), Giyan VA (4800–4500 BC)				

8.7 and 8.8 at trench JIII, Kambakhsh-Fard, 1994, pp. 234–235). Evidence of seismic destruction includes: (i) deformation of the Parthian coffins, (ii) destruction of the southern section of the temple where a pair of opposed staircases had acted as buttresses to the columned southern wall, (iii) destruction of the Sassanid Chahar Taq Fire Temple (c. 224–636 AD) situated on the uppermost platform, (iv) displacement and fracturing of heavy stones along the pair of opposed staircases, (v) repairing of broken and fractured stones with metal clamps at the southwestern section of the Temple, (vi) draping of heavy stone rows, and (vii) flinging of the stone columns 10–17 m away from their original sites (A. Kabiri, personal communication, 27 April 1999). This evidence suggests that the destruction was caused by a large-magnitude earthquake along the Dinevar–Nahavand section of the ZMRF.

Many of the dressed stone blocks of this period bear graffiti and masons' marks of the Sassanid period, and were apparently used in rebuilding in the mid-Sassanid period during the reign of King Piruz (AD 459–485) (Kambakhsh-Fard, 1971, 1972, 1973, 1974, 1994, 1995; Matheson, 1976). Kambakhsh-Fard (1974) and Matheson (1972, 1976) suggested destruction of the Temple by a strong earthquake, although in a subsequent paper, Kambakhsh-Fard (1994) did not mention an earthquake in discussing the major rebuilding activity. If it was an earthquake, it occurred after the earliest Sassanid date for the Chahar Taq Fire Temple (AD 224) and before the rebuilding of King Piruz, i.e. c. AD 224–459, assuming that this long reconstruction project was ordered by the King after his inauguration (Table 1). During the Sassanid period, the Sarmaj Fort at the nearby city of Dinevar (the ruins of which are located between Zibaju and Sheikhkhan villages) was also repaired (Rozhbaiany, 1996); however, the reason for the repair is not known (Fig. 2).

2.3. The 1008 and 1107 earthquakes at Dinevar

Apparently, springs of the Anahita Temple at Kangavar dried up toward the end of the Seljuq period (c. early 13th century AD) (Kambakhsh-Fard, 1994). Although there is no written record of an earthquake at Kangavar in this period (Table 1), the drying up of springs could have been related to historical earthquakes in AD 1008.04.27 and AD 1107.09.00 that affected Dinevar, the capital city of the Amir Hassaniyeh Kurdish tribe, located 42 km west of Kangavar (Fig. 2). The AD 1008 ($M \sim 7.0$) earthquake resulted in at least 16,000 dead with additional losses from co-seismic landslides, and the earthquake may have been associated with ground deformation (al-Antaki, 1066; ebn al-Jauzi, 1181; ebn al-Athir, 1231; Bar Hebraeus, 1286; al-Dhahabi, 1315; al-Suyuti, 1499; ebn al-'Emad, 1670; Ambraseys and Melville, 1982; Berberian, 1995a). The Kargsar–Dinevar region was also severely damaged during the AD 1107 ($M \sim 6.5$) earthquake, and a large number of people perished (al-'Omari, 1793; Ambraseys and Melville, 1982; Berberian, 1995a,b) (Table 1 and Fig. 2).

Huge columns from the Anahita Temple with Qezelbash (Safavid: AD 1491–1722) graffiti have fallen down in the northwestern part of the Temple (A. Kabiri, personal communications, 1990 and 27 April 1999), but this destruction could have had a non-earthquake origin.

2.4. Discussion on the activity of the Zagros Main Recent Fault

Major earthquakes in the Dinevar–Nahavand region around 1650–1600 BC and AD 224–459 may have involved motion along the ZMRF. The postulated 1650–1600 BC Godin and AD 224–459 Kangavar earthquakes are separated by 1800–2100 years, and the more recent event is older than the AD 1008 historical earthquake by 500–800 years. The AD 1008 and AD 1107 earthquakes at Dinevar may have ruptured two different strands of the ZMRF (possibly the Dinevar and Sartakht segments; Fig. 2). The time interval between these earthquakes can only be stated as 850–950 years. The intervals of 500–800 and 850–950 years are in the same range, and are about half the interval after the 1650–1600 BC earthquake. This could be a real difference, or there may be an undetected earthquake after the 1650–1600 BC Godin event. Future archaeological excavations at Sarab, Bozorg-e-Sahneh, Chogha Kabud, and other nearby mounds (Fig. 2) may add to the record if, unlike Godin and Giyan, they contain an archaeological record from the first millennium BC. There are two other major cultural gaps of unknown origin around c. 1900 BC and c. 2150 BC at both Godin and Giyan mounds (Henrickson, 1986).

3. The Ipak Fault (northern central Iran)

About 120 km west of Tehran (Fig. 1), the 1962.09.01 Bo'in Zahra earthquake of M_s 7.2 (M_w 7.0) destroyed 91 villages, killing 12,200 people and injuring 2800. Over 21,300 homes in 300 villages were damaged beyond repair or partially destroyed, 180 of them with loss of life (Ambraseys, 1963).

The earthquake was associated with 95 km of surface rupture along the Ipak reverse fault (Fig. 3) with average throw of 140 cm and left-lateral displacement of 60 cm (Ambraseys, 1963; Berberian et al., 1983, 1993). The WNW–ESE-trending Ipak reverse fault consists of multiple segments connected in a complex network (Fig. 3). The reverse fault segments dip both south and north. The 56-km-long eastern section strikes E–W, N105°E and N70°E and dips south, while the 39-km-long western section strikes N110°E and N120°E and dips north (Fig. 3). This indicates that the co-seismic north- and south-dipping reverse faults were related structures in a zone 10 km wide (Berberian et al., 1983, 1993). Because of this interaction, the VIII (MMI) isoseismal makes a left step to encompass north- and

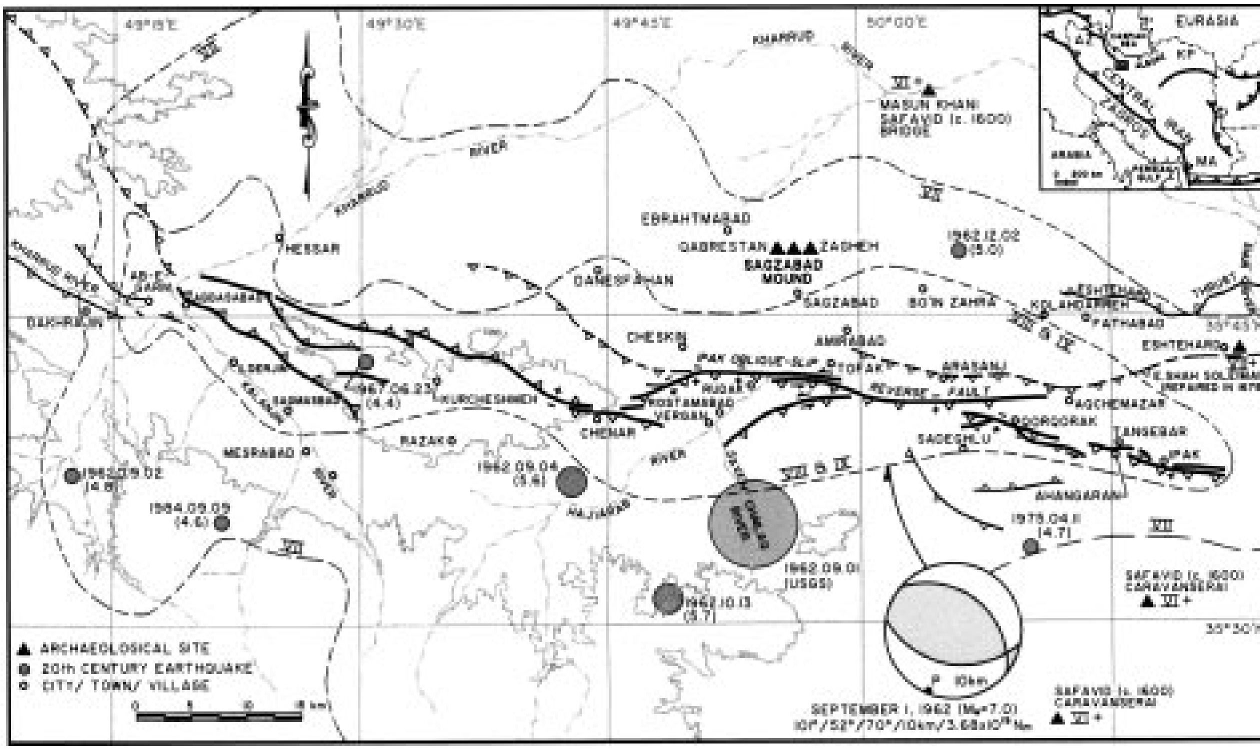

Fig. 3. Location of active reverse fault of the AD 1962 (M_w 7.0) earthquake with isoseismal lines, and archaeological sites adjacent to the fault. The 1962 earthquake rupture is shown by a thicker line. The area has entered a relative quiescent period since the 1962 event, during which only two low-magnitude earthquakes were recorded. Fault map revised from Berberian et al. (1983). The 1962 earthquake isoseismal lines are taken from Ambraseys (1963). Fault plane solution after Priestley et al. (1994). Source mechanism data: strike/dip/rake/centroid depth/M_o. Fault symbols are as in Fig. 1. The USGS epicenters (circles with date and magnitude) for the early days of the WWSSN has unknown magnitude of location errors, especially for the low- and medium-magnitude events. E = Emamzadeh (shrines for local Shiite Muslim saints); they are usually modest, circular, four-sided or octagonal buildings surmounted by a cone or dome. Map located in Fig. 1.

south-dipping reverse faults (Fig. 3). The fault-plane solution of the main shock (Petrescu and Purcaru, 1964; McKenzie, 1972; Priestley et al., 1994) shows mainly thrusting.

There were no important historical monuments in the meizoseismal area of the AD 1962 earthquake. A number of Safavid structures (c. AD 1600) such as bridges, carvanserai, and mausoleums (Fig. 3) suffered minor damage (VII+ at Shah Soleiman mausoleum in the east; VI+ at Masun Khani bridge in the north, and VI+ at a caravanserai in the southeast; Fig. 3), indicating a minimum quiescent period of about 400 years.

3.1. The c. 2000–1500 BC event at Sagzabad mound

The archaeological mound of Sagzabad, located 14 km north of the Ipak fault (Fig. 3), lies within the I_o = VII+ (MMI) isoseismal line of the AD 1962 earthquake. 'Trial-trenching' revealed 36 levels dating from the first half of the fourth millennium BC to Achaemenid times (550–330 BC). 'Trial-Trench B' at level 9 (late third millennium BC) on the eastern wall of Sagzabad (Table 2) revealed many "complete but crushed skeletons of domesticated animals, lying side by side under collapsed walls, as though they had perished in a stable that had been destroyed by some natural calamity such as a flood, or more likely, an earthquake" (Negahban, 1971, 1973, 1974a,b, 1976, 1977). Excavation of the Sagzabad mound also shows displacement of a charcoal layer (not dated) and rotation of blocks in alluvial deposits (see fig. 8.1, p. 103 in Berberian et al., 1983, 1993). More recent excavations (Tala'i, 1998) revealed: (i) a Late Bronze Age (c. 2000–1600 BC) square brick column collapsed toward the NW (in 'Trench 700'), (ii) tilting of a Late Bronze Age wall toward the SW, and (iii) NW–SE fracturing of an area approximately 2000 and 3000 m^2, splitting a pottery vessel embedded in the floor into two pieces [from 'Trench NXX' to 'Trench OXX' in the Late Bronze age layers (c. 2000–1600 BC) to the Early Iron age (c. 1450 BC) (H. Tala'i, personal communication, 25 April 1999)]. If this deformation was caused by an earthquake, it occurred in c. 2000–1500 BC.

3.2. Discussion on the activity of the Ipak Fault

Archaeological evidence at Sagzabad mound reveals a possible large-magnitude earthquake around 2000–1500 BC, which may have involved motion along the Ipak Fault. The magnitude of the postulated Sagzabad earthquake is not clear, since we have data from only one site and there is, therefore, no indication of the size of the destroyed area.

Table 2
Summary of archaeological, architectural, and earthquake information of the Sagzabad, Qabrestan and Zagheh mounds, adjacent to the Ipak Fault (see Fig. 3)

Years BC	Zagheh	Qabrestan	Sagzabad Test Trench OXX	Sagzabad Test Trench B	Earthquakes
					1962.09.01(7.2) Bo'in Zahra [VII+ at Sagzabad, Qabrestan, & Zagheh mounds]
0			?	?	
500			19	1	
1000			11	2	
1500			6	5	
				8	
2000			3	9	c. 2000-1500 BC Sagzabad ?
2500			2	The lower level (2050 BC) is laid over virgin soil	
3000					
		Gh.IV:3-1			
		Gh.IV:6-4			
		Gh.III:8-7			
		Gh.II:10-9			
3500					
4000		Gh.I:19-11	1		
		«Gap»	?		
4500		Late Ch.'Ali			
	I	Early Cheshmeh 'Ali			
5500					
6000	VIII	?			
	IX				
7000	XII				
	?				

However, the intensity of the c. 2000–1500 BC Sagzabad event is possibly close to that of the AD 1962 earthquake along the Ipak reverse fault. Motion along only the segment of the Ipak Fault closest to the mound (i.e. the Rudak fault segment, 14 km away with a length of 18 km) would not have been capable of creating an earthquake with intensities of VII+ (MMI) and VIII (MMI) at Sagzabad. Therefore, we rule out motion on only a single segment of the Ipak Fault during the c. 2000–1500 BC event. The Ipak Fault is the only one close enough to the Sagzabad mound to be a candidate fault for the postulated earthquake destroying Sagzabad (Fig. 3) and no geomorphic evidence of active folding above a blind thrust is present. We suggest that the AD 1962 earthquake may be a repeat of the c. 2000–1500 BC postulated earthquake, giving a 'maximum recurrence interval' of approximately 3500–4000 years for the Ipak Fault.

Three hundred meters to the west of the Sagzabad mound is the Qabrestan [lit.'Cemetery'] mound (Fig. 3 and Table 2), where a settlement extended from the mid-sixth millennium BC to the early fourth millennium BC, with one major gap of 500 years between 4500 and 4000 BC (Negahban, 1974b; Majidzadeh, 1976, 1977, 1981). The Qabrestan mound was abandoned permanently around the beginning of the fourth millennium BC, which would have been prior to the c. 2000–1500 BC earthquake at Sagzabad. The effect of the Sagzabad event was overlooked in 'Trial-Trench' OXX at Sagzabad (E. Negahban and H. Tala'i, personal communications, April 1999) (Fig. 3 and Table 2). The Zagheh (Malek Shahmirzadi, 1995) and Qabrestan mounds predate the postulated Sagzabad earthquake, and the ground shaking effect of this event (as well as the AD 1962 event) on these mounds was not considered.

4. The Rudbar Fault (western Alborz Mountains)

In the western Alborz Mountains, southwest of the Caspian Sea, the 1990.06.20 Rudbar–Tarom earthquake of M_w 7.3 killed approximately 40,000 people and destroyed three cities and 700 villages (Berberian et al., 1992). The

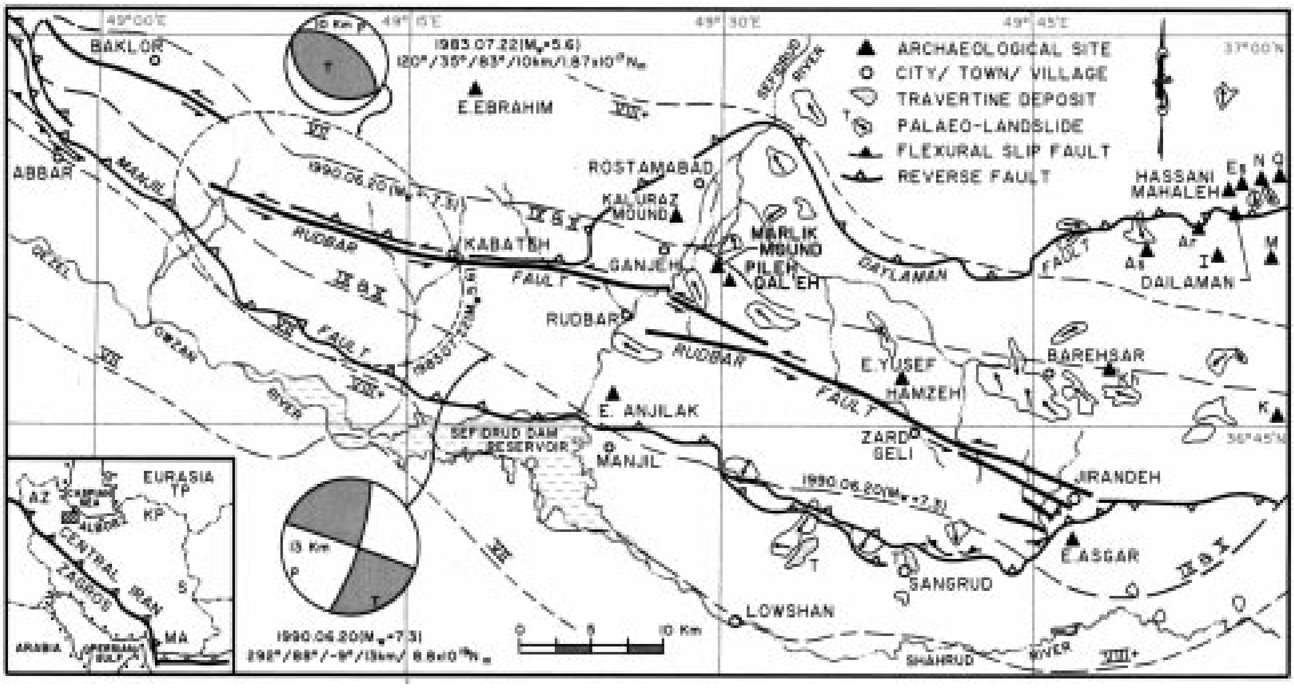

Fig. 4. The AD 1990 Rudbar left-lateral strike-slip earthquake fault, isoseismal map of the 1990 M_w 7.3 earthquake (intensity IX–X and VIII$^+$) and the 1983.07.22 M_s 5.6 (intensity VII), and location of the Marlik and other archaeological mounds adjacent to the fault (revised after Berberian et al., 1992). The 1990 earthquake rupture is shown by a thicker line. Fault plane solutions after Berberian et al. (1992) and Priestley et al. (1994). Fault symbols are as in Fig. 1. Source mechanism data: strike/dip/rake/centroid depth/M_0. Ar = Aushki; As = Asiabar; E = Emamzadeh/Shrine; Es = Espeli; I = Ishehkuh; K = Kelishom; Kh = Khoshkushan; M = Mulameh; N = Nauruz Mahaleh; Q = Qaleh Kuti. Map located in Fig. 1.

earthquake was accompanied by 80 km of left-lateral strike-slip faulting along the Rudbar Fault. The co-seismic surface faulting was located only in a limited reconnaissance, and displacements on the fault were observed at only a few localities. The Rudbar Fault consists of the Baklor, Kabateh, and Zard Geli segments in a right-stepping en échelon pattern, with strike from 090° to 120° and dips steeply SSW to nearly vertical. Maximum displacements of 60 cm left-lateral and 95 cm vertical were observed along the southeastern (Zard Geli) and the central (Kabateh) segments. Vertical displacements were consistently down to the north and northeast, in the opposite sense to the local topographic slope.

4.1. The c. 1000–800 BC event at Marlik mound

The Marlik archaeological site, 3.5 km north of the Rudbar Fault, underwent intensity of IX (MMI) during the 1990 event (Fig. 4). This site is in a fertile region southwest of the Caspian Sea that was occupied by the ancient Marlik culture (~1300–800 BC), which abruptly declined in the early part of the first millennium BC, when the Marlik people suddenly left the region. A comparison of Marlik vessels with comparable objects found in other excavations supports the time range of late second millennium BC and early first millennium BC for the Royal Cemetery of Marlik. This date is consistent with a date of 1457 BC ± 55 years (Negahban, 1990, 1996) from the wooden handle of a dagger collected from the Marlik tomb (XV-D Instituut Voor Prehistorie Der Rijksuniversiteit te Leiden, Groning C-14 Laboratory, Leiden, 15 January 1968).

Excavation of the Royal Necropolis of Marlik revealed broken pottery and other disturbed objects, dented and crumpled metal vessels, an overturned gold vessel, and broken, displaced and rotated stone slabs beneath buried human remains (Negahban, 1964, 1984, 1990, 1996; E.O. Negahban, personal communication, 15 November 1990), consistent with strong ground shaking accompanying a large-magnitude earthquake in the ninth or 10th century BC. According to Negahban (1996): “in some tombs the arrangement of the objects was badly disturbed by a different or slanting floor, which was apparently the result of a major disturbance to the mound, possibly from an earthquake or the sinking of the ground” (see plate 8D, tomb 26, trench XVIIB, in Negahban, 1996). “The contents of this tomb (#26) were badly disturbed when found, possibly by an earthquake or other natural action, and they were not in a horizontal layer as was the case in some of the other tombs”. In tomb 32, Negahban (1996) observes that “several layer slabs of stone were placed above and around each other on the floor of the tomb 32 with crushed objects in between [see plate 10C in Negahban (1996)], suggesting that there may have been some sort of disturbance to the tomb to bring such disorder to the contents. This disturbance may have been an earthquake or other natural action with no

Table 3
Summary of archaeological, architectural, and earthquake information of the Marlik and Kaluraz mounds, adjacent to the Rudbar Fault (see Fig. 4)

Years AD/BC	Marlik	Pileh Qa'eh	Kaluraz	Earthquakes
				1990.06.20 (7.4) Rudbar-Tarom
	-	?	-	
c.AD 1,000	-	17: Repair on the Sassanid fort & continued use until the 11th century	-	
636-642	Invasion of Arabs			
AD 224-636	-	15-16: Sassanid fort on top of the mound	-	
BC:	-	?	-	
600		?	Kaluraz Culture	
800	c.800 BC: Sudden abandonment of the site	13-14: Malik period		**c. 1000-800 BC Marlik (?)**
1000				
1100	Marlik Culture			
1200			-	
1300	-	8-12: late 2nd to early 1st millennium BC	-	
	-	1-7: early to late 2nd millennium BC	-	
2,000				

connection to tomb robbery, for valuable contents of the tomb remain".

The disturbed remains in the Marlik mound constrain the maximum age of this earthquake. The date of the sudden abandonment of the site and comparison with sites to the north, farther away from the Rudbar Fault, give a minimum age for the event, and date the postulated event around c. 1000–800 BC. However, even though the damage appears to be earthquake related, it is not known that the abandonment of the site was due to the earthquake.

The sudden migration of the Marlik people presumably occurred before the development of the Bronze Age civilization of the Kaluraz mound, 5 km west northwest of Marlik and 5 km north of the Rudbar Fault (Fig. 4 and Table 3), during the first half of the first millennium BC (c. 1250–700 BC; Hakemi, 1968), and before the Bronze Age/Partho-Sassanid tombs of Hassani Mahaleh (Sono and Fukai, 1968). The rise of these cultures with no evidence of reported damage may indicate that there was no catastrophic earthquake in the Marlik area at least from c. 800 BC to Partho-Sassanid times (c. AD 230). The absence of any historical evidence for an earthquake prior to AD 1990 may suggest that there was no earthquake between the time of damage to the Royal Necropolis of Marlik and the 1990 earthquake.

The size of the postulated c. 1000–800 BC Marlik event is not known, since evidence from only a single archaeological site provides no indication of the size of the destroyed area. However, the high intensity indicated by the ruptured, displaced thick stone slabs beneath the buried bodies suggests that the Marlik event was likely a large-magnitude earthquake on a nearby fault with magnitude possibly similar to that of the AD 1990 earthquake. A 'trial-trench' at Pileh (Pila) Qal'eh mound, 500 m southeast of Marlik, revealed the Sassanid (AD 224–642; 'layer-16'), Marlik (~1300–800 BC; 'layers 13 and 14'), and early to late second millennium BC layers ('layers 1–12'). The excavation was limited, with no consideration of strong ground motion (Kambakhsh-Fard, 1991; Negahban, 1996; E.O. Negahban, personal communication, 20 April 1999). Systematic excavation of this and other archaeological sites around Marlik may elaborate the record significantly.

4.2. Discussion on the activity of the Rudbar region

Evidence for strong shaking at the Marlik mound in the Rudbar area and the absence of reported evidence for strong shaking at Kaluraz (5 km north of the Rudbar fault) and Hasani Mahaleh mounds suggest a possible major earthquake around 1000–800 BC. Because Marlik is located in an area also characterized by active reverse faults, the association of the ancient event with reactivation of the Manjil Fault or a blind thrust cannot be ruled out (Fig. 4). The Rudbar strike-slip fault is only 3.5 km south of the mound. The closest reverse fault (Daylaman; Fig. 4) is located approximately 10.5 km north of the mound, and

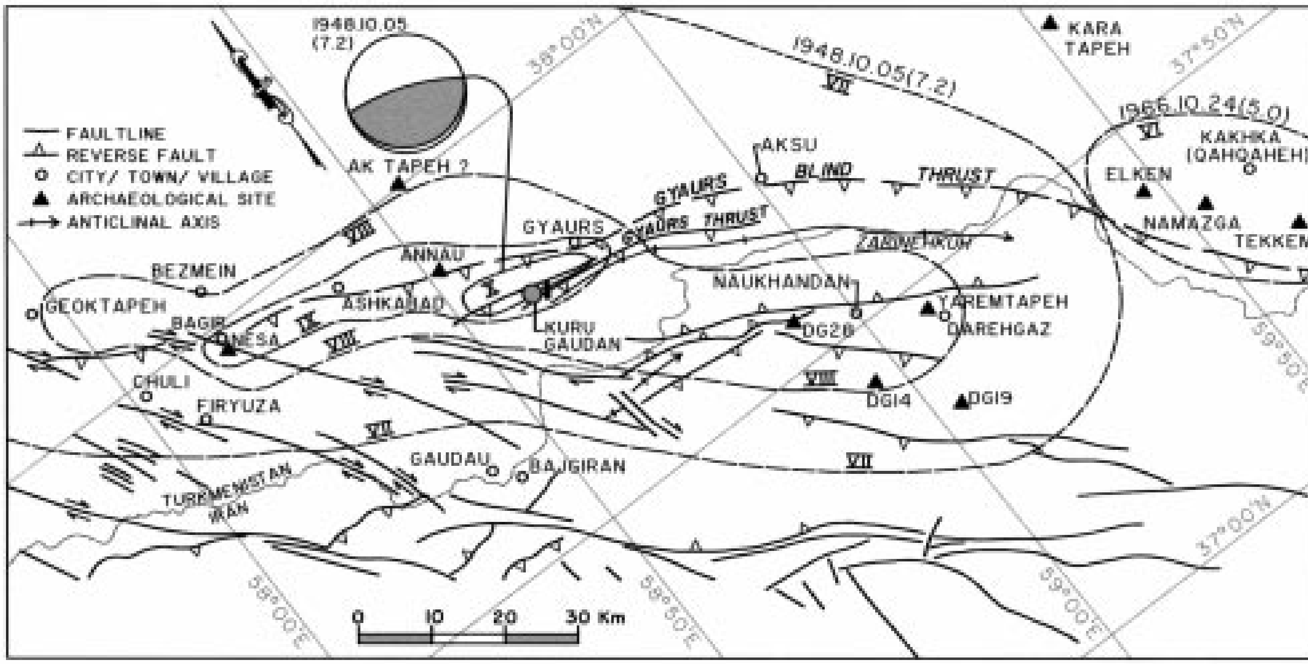

Fig. 5. Active tectonic map (located in Fig. 1) of the Ashkabad area. Faults are drawn from the satellite imagery (Landsat-TM, 160 and 161/034, 1987, 1988). Isoseismals (MSK) of the 1948 (M_s 7.2) earthquake in Turkmenistan based on Medvedev (1955) and Gorshkov (1957), Medvedev (1961), and in Iran, based on Tchalenko (1975) and this study. The approximate location of the co-seismic extension surface fractures is shown by a thick line striking N30°E east of Kuru Gaudan village (large circle) on the Kuru Gaudan–Zarineh Kuh anticline above the hanging wall block of the Gyaurs surface thrust and blind thrust faults. Fault plane solution of the AD 1948 earthquake after McKenzie (1972). Meizoseismal area of the 1966 earthquake at Kakhka (Qahqaheh, NE of Namazga mound) after Bune and Gorshkov (1980). Archaeological sites (Kohl and Heskel, 1980; Zadneprovsky, 1995) are shown by filled triangles. Fault symbols are as in Fig. 1. Exact location of Ak Tapeh mound is uncertain, since Kondorskaya and Shebalin (1977, 1982) locate it to the NW of Ashkabad, while Golinsky (1977, 1982) locates it 18 km NE of Ashkabad (we choose the latter).

the Manjil reverse fault is located 12.5 km to the south of the mound (Fig. 4). Accordingly, the 3000-year 'maximum recurrence interval' refers to the region (an 'area source'), since the earlier earthquake could have ruptured one of the reverse faults rather than the Rudbar strike-slip fault. Rupture of the Daylaman reverse fault during this period is less likely because no disruption is reported from Hassani Mahaleh mound located about 1000 m north of the fault (Fig. 4). We cannot prove that this site was in continuous occupation and undamaged throughout the 3000-year time interval.

5. The main Kopeh Dagh Fault system (Turkmenistan)

Ashkabad, the capital city of Turkmenistan, was destroyed by an earthquake of M_s 7.2 in 1948.10.05 (Fig. 5). More than 10,000 people were killed in Turkmenistan, and more than 30 villages were destroyed in Iran, with more than 350 people killed in the Dareh Gaz region alone. The earthquake had an intensity of IX (MSK) at Ashkabad, Nesa, and Annau (Fig. 5), and X (MSK) at Kuru Gaudun and Gyaurs (Gorshkov, 1957). This was the strongest earthquake to strike this region since at least AD 1455, the year that the Timurid Shrine of Shaykh Jamal al-Din was built at Annau (Golombek and Wilber, 1988), 14 km ESE of Ashkabad (Fig. 5). This shrine was reduced to a small group of isolated piers in AD 1948.

Although the intensity IX (MSK) isoseismal of the AD 1948 earthquake has the form of an NW–SE elongated ellipse parallel to the foothills of the Kopeh Dagh mountains, the NW–SE mountain-bordering strike-slip faults were not reactivated at the surface (Gorshkov, 1957; Koridalin et al., 1961; Medvedev, 1961; Rustanovich and Shirokova, 1964). The X and IX (MSK) isoseismals, located on the hanging wall block of the Gyaurs surface thrust and blind thrust, follow the trend of the Gyaurs surface fault. However, the VIII (MSK) isoseismal in Iran makes a right step to encompass the Naukhandan thrust fault, as if the motion was transferred from one fault to another (Fig. 5; also compare with the Ipak case in Fig. 3). The absence of surface rupture may have been due to the absorption of brittle faulting by ductile beds, a deeper focal depth, or a blind reverse fault. Tension fissure zones hundreds of meters long and approximately 30 m wide striking N30°E were found at Kuru Gaudan (Fig. 5) 28 km SE of Ashkabad (Gorshkov, 1957; Koop et al., 1964; Gorshkov and Yakushova, 1967; Tchalenko, 1975).

An NNE–SSW shortening in the southeastern section of the meizoseismal area, in the hanging wall block of both the Gyaurs blind and surface thrust faults (Fig. 5), is indicated by: (i) development of an E–W elongated maximum intensity of X (MSK) in the area south of Annau–Kuru Gaudan–Gyaurs with N30°E tension fractures at Kuru Gaudan (Medvedev, 1955; Gorshkov, 1957; Rezanov, 1959; Rustanovich, 1967); (ii) buckling to a height of 1 m of the water pipes in several places in Kuru Gaudan village, with telescoping of one pipeline over a length of 3 m (Butovskaya and Kovalenko, 1955); (iii) flinging of the roofs from cattle sheds to a distance of several meters in an NE–SW direction (Butovskaya and Kovalenko, 1955); and (iv) a 22-cm subsidence of the Trans-Caspian Railway based on re-leveling at Gyaurs (Butovskaya and Kovalenko, 1955; Kolibaev, 1962).

The Kuru Gaudan surface ruptures striking N30°E were developed approximately perpendicular to the Kuru Gaudan–Zarineh Kuh anticlinal axis (striking NW–SE) on the hanging wall of the Gyaurs thrust (Fig. 5). This suggests that the fissures were surficial extension fractures and faults developed on the hanging wall of the Gyaurs blind thrust as the Kuru Gaudan–Zarineh Kuh anticline was folded during the 1948 earthquake. The Kuru Gaudan–Zarineh Kuh anticline is an asymmetric fold with a steeper dip along the northeastern faulted flank (the Gyaurs surface fault in Turkmenistan), a shallower dip along the southwestern flank (in Iran), and plunging ESE in Iranian territory. Pleistocene loess deposits covering the southeastern section of the anticline axis in Iran are now at an elevation of +997 m, about 317 m higher than loess deposits in the area east of Dareh Gaz (Fig. 5), where the nose of the anticline plunges under the loess deposits of the plain (+688 m). The association of the Kuru Gaudan–Zarineh Kuh fold with the Gyaurs blind thrust suggests that it is a fault-propagation fold. The relative subsidence of the plain north of the Kopeh Dagh mountain is recorded by alluviation and burial of the lower cultural levels of major prehistoric mounds such as Namazga and Kara Tapeh (Fig. 5) beneath several meters of alluvial deposits. Virgin soil was reached at 11.5 m beneath the present surface of the plain in the southern Trench No. 2 at Namazga (Namazga-I ~5000 BC, which gives a deposition and/or subsidence rate of 1.6 mm/year), 3 m below Namazga-IV (3000–2500 BC; 0.6 mm/year), and 8.5 m below Namazga-III (3500–3000 BC; 1.5 mm/year) deposits (Kuftin, 1956; Kohl and Heskel, 1980; F.T. Hiebert, personal communication, 2 May 2000). The map showing the total vertical crustal displacement during the Neogene and Quaternary (Czovsky et al., 1960) clearly records the subsidence of the Kopeh Dagh foredeep (the Ashkabad plain) and uplifting of the Kopeh Dagh mountain belt.

A poorly constrained fault-plane solution for the AD 1948 earthquake (McKenzie, 1972) shows a thrust mechanism with an almost shallow plane dipping SSW. This mechanism agrees with that of Rustanovich and Shirokova (1964), who combined this solution with the results of leveling lines to show that the shallow plane dipping SSW was the fault plane (Fig. 5). Rezanov (1959) and Rustanovich (1967) proposed a shallow SSW dipping fault at the contact of Mesozoic and Paleozoic deposits in the Kopeh Dagh foredeep, 10 km below the Ashkabad–Bezmein plain.

Despite the low accuracy of the locations, the two aftershock studies based on temporary networks in 1949 and 1953 indicated that the majority of the shocks were located at 10–20 km depth, concentrated near the NW and SE ends of the zone of maximum destruction in Turkmenistan, at Kuru Gaudan (in the SE) and Bezmein (in the NW) (Rustanovich, 1957; Koridalin et al., 1961; Puchkov, 1961; no aftershock record is available from the Iranian side). This and the re-triangulation results of 178- to 190-cm right-lateral displacement at Ashkabad (Butovskaya and Kovalenko, 1955; Kolibaev, 1962) suggest that the AD 1948 earthquake, with reverse surficial deformation at Kuru Gaudan, was also associated with right-lateral strike slip along the Main Kopeh Dagh Fault system at depth. The Main Kopeh Dagh Fault consists of several partly overlapping segments parallel to the overall NW–SE structure with stepovers. The regions of overlap are characterized by shorter south-dipping thrust faults striking about E–W (Fig. 5). Trifonov (1978) reported active displacement along the Main Kopeh Dagh Fault for more than 500 km, with right-lateral displacement of 30 cm and 10 m of the walls and the nearby qanats (traditional underground water canals) of the Parthian palace of Mithradatkert (Nesa). He estimated right-lateral Holocene displacement of 8 m, and Holocene–Late Pleistocene displacement of 55–60 m along the Main Kopeh Dagh Fault.

5.1. The c. 10 BC–AD 10 event at the capital city of Mithradatkert (Nesa mound)

The present Nesa mound, the ancient Mithradatkert, located 17 km west of Ashkabad and 8 km south of Bezmein (Fig. 5) is the site of the capital city of the Parthyene District of the Parthian Empire (second century BC to third century AD) of ancient Persia. A palace, a cathedral, and two mausoleums were excavated in the destroyed fort of Mithradatkert. The upper part of a pyramid-stepped tower in the mausoleum at Mithradatkert was found torn from the wall so that the tower had collapsed. Two of the three columns supporting the roof of the hall had fallen; the top part of the third one and the remaining part of the shaft had been tilted to one side. The inner part of the east wall, with half-columns standing alongside it, was found tilted toward the middle of the hall. The interior was filled with roof beams and fallen debris from the upper part of the mausoleum (Gorshkov, 1947a,b). This destruction near the beginning of the Christian era, which totally destroyed the capital city of Mithradatkert, is attributed to a strong earthquake. Judging from the position of the fallen and displaced column shafts, the direction of tilt of the towers, and the inner parts of the east wall, the basic direction of ground shaking was estimated to be approximately east to west (Golinsky, 1977). The earthquake occurred in 10 BC (Ambraseys and Melville, 1982) or 10 AD (±100 years) (Kondorskaya and Shebalin, 1977, 1982; Golinsky, 1977, 1982; Bune and Gorshkov, 1980). The Russian estimated magnitude was $M_s \sim 7.1$, with an intensity of $I_o \sim$ IX–X (MSK) and epicenter at 38.0°N, 58.3°E (Fig. 5).

According to Gorshkov (1947a,b), the mausoleum at Mithradatkert was constructed in the middle of the third century BC. The hall, covered by colored plaster and connected to the palace nearby, was built in the middle of the first century BC. The fort of Mithradatkert was the place of burial of the earlier Arshakid rulers of Iran from the middle of the third century BC to the end of the first century BC. The later Arshakids came to power in the year 10 AD and the destruction of Mithradatkert capital city was not related to this incident. The mausoleum of the dynasty founders, the earlier Arshakids, was partially cleared after their burial, and, like the rest of this group of buildings, was not restored. The lack of restoration leads to the conclusion that the destruction of the Mithradatkert fort by the earthquake dates from the time when the first representatives of the later branch of the dynasty replaced the earlier Arshakids: between the last years of the first century BC and the first years of the first century AD (Gorshkov, 1947a,b; Golinsky, 1977, 1982). Pugachenkova (1972) places the earthquake in the fifth century AD, which is too recent, and has not been accepted by Russian archaeologists.

5.2. The c. 2000 BC event at Ak Tapeh mound

Remains of a collapsed and burned brick building were found in AD 1931 at Ak Tapeh mound (38.1°N–58.5°E; located in Figs. 1 and 5), 18 km northeast of Ashkabad (Gorshkov, 1947a,b). Archaeological investigations indicated that people had abandoned Ak Tapeh unexpectedly, with untouched food in an alabaster dish, a skeleton of a man trapped by the collapsed building, and traces of fire caused by the roof collapsing into the fireplaces. Several large clay vessels that had fallen were exhumed in a room; they were all leaning to the west (Golinsky, 1977, 1982; Kondorskaya and Shebalin, 1977, 1982; Bune and Gorshkov, 1980). The total destruction of the Ak Tapeh structure was considered to be caused by a large-magnitude earthquake ($M_s > 7.0$) around c. 2000 BC (±100 years) (Kondorskaya and Shebalin, 1977, 1982; Ambraseys and Melville, 1982; Berberian, 1995a).

5.3. Discussion on the activity of the Main Kopeh Dagh Fault system

There is archaeological evidence for large-magnitude earthquakes in the Ashkabad region around 2000 BC and 10 BC–AD 10. These earthquakes and AD 1948 (M_s 7.2) event suggest a 'maximum recurrence interval' of about 2000 years. The major identified fault in the region is the Main Kopeh Dagh Fault system (right-lateral fault with related thrust faults), which is possibly the source of the two earlier earthquakes as well as the AD 1948 event.

There is a cultural gap of unknown origin around 3600–3200 BC in archaeological layers in Annau mound (14 km southeast of Ashkabad; Fig. 5) between 'Annau-II' (c. 4000–3600 BC) and 'Annau-III' (c. 3200–2700 BC) (Crawford, 1963; Kambakhsh-Fard, 1991). The time interval between the c. 2000 BC earthquake and this cultural gap is 1200–1600 years. Detailed investigation at 32 prehistoric mounds located to the southeast of Ashkabad in Turkmenistan (including Yarem Tapeh) at Dareh Gaz in Iran (Fig. 5), Annau, Namazga (third millennium BC; 105 km SE of Annau), Elken (second millennium BC; 97 km SE of Annau), and Altyn (third millennium BC; beyond the eastern limit of Fig. 5; see Fig. 1) may elaborate the record significantly. For unknown reasons, both Altyn and Namazga mounds fell into decay and the populations dwindled during the second millennium BC (Namazga-V and end of Namazga-VI, respectively; Zadneprovsky, 1995). In approximately 2000 BC, the principal cities of the area were abandoned (Biscione, 1977; Kohl, 1984). Kara Tapeh mound (Fig. 5) was permanently abandoned in the late fourth or early third millennium BC (Kohl and Heskel, 1980) for unknown reasons.

Since the partitioned deformation between active right-lateral strike-slip and thrust faults characterizes the northeastern edge of the Kopeh Dagh Range, the 2000-year 'maximum recurrence interval' refers to an 'area source' instead of the Main Kopeh Dagh right-lateral fault itself. The northeastern edge of the Kopeh Dagh Range accommodates a combination of NW–SE right-lateral shear and NE–SW shortening along thrust faults between the Turan Block (Karakum Platform) and the Kopeh Dagh mountain belt. The NW–SE right-lateral Main Kopeh Dagh Fault is not a continuous fault. The fault has several segments and stepovers, and toward their ends, they splay into or end at thrust faults, which die out with distance from the strike-slip fault segments. The high topography is usually associated with the junction of the strike-slip and thrust faults, with the elevation decreasing away from it. Similar structures were examined elsewhere (Bayasgalan et al., 1999; Berberian et al., 1999, 2000).

6. Earthquakes affecting the Qa'en Friday Mosque, in Qohestan Province (southern Khorasan)

A 20th century AD earthquake cluster in the Qa'en/Dasht-e-Bayaz area consisted of 11 earthquakes of $M > 6.0$ in 61 years (AD 1936–1997; Berberian and Yeats, 1999). None of these events caused destructive intensities at the Qa'en Timurid Friday mosque (AD 1368). However, both the archaeological and recorded history show destruction of an earlier mosque at the same location by a strong earthquake in May AD 1066. Since earthquakes during the period AD 1066–1900 did not

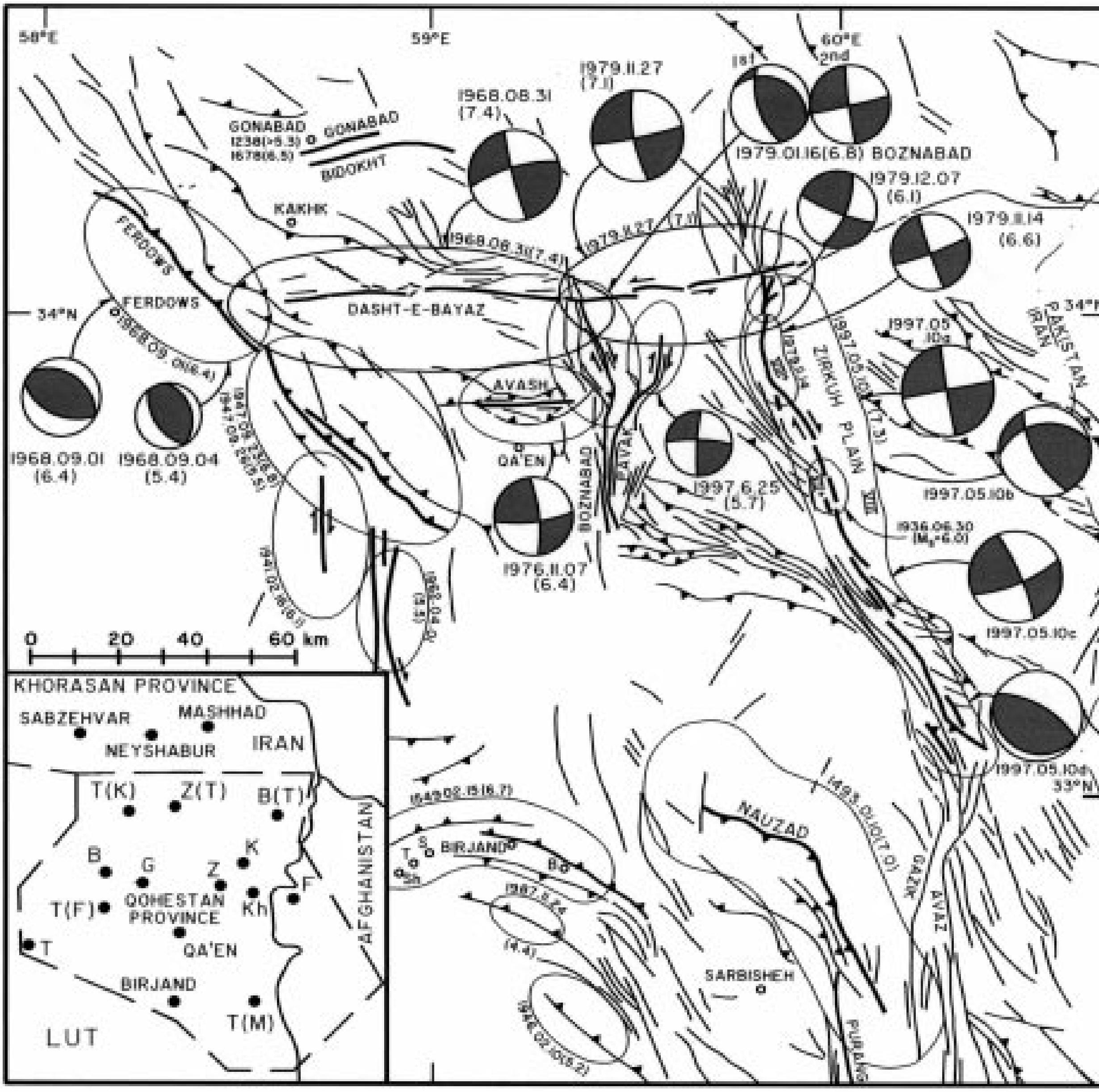

Fig. 6. Fault/seismicity map (located in Fig. 1) of the Qa'en area (modified after Berberian and Yeats, 1999; Berberian et al., 1999). The 1979.01.16 (6.8) Boznabad focal mechanism solutions with two subevents (first and second) are from Baker (1993), and the 1997.05.10 (7.3) Zirkuh focal mechanisms with four subevents (a, b, c, and d) are from Berberian et al. (1999). Fault symbols are as in Fig. 1. Destroyed villages in the meizoseismal area of the 1549.02.15 earthquake: B = Bozhd; S = Siojan; Sh = Shahzileh; T = Taqab. Inset bottom left: the Qohestan province of eastern Iran, south of the Khorasan province during the 15th century AD. The present border between Iran, Afghanistan and Turkmenistan is marked by a continuous line. B = Bajestan; B(T) = Buzjan (now Torbat Sheikh Jam); F = Farjerd; G = Gonabad; K = Khaf; Kh = Kharjerd; S = Sabzevar (the ancient Beihaq in the Khorasan province north of Qohestan); T = Tabas-e-Gilaki (now Tabas-e-Golshan); T(F) = Tun (now Ferdows); T(K) = Turshiz (now Kashmar); T(M) = Tabas-e-'Anab (now Tabas-e-Masina); Z = Zowzan; Z(T) = Zaveh (now Torbat Heydariyeh).

damage the mosque, we suggest that no pre-1900 earthquakes are a repeat of the 1066 earthquake at Qa'en.

6.1. Recorded and archaeological evidence of the May AD 1066 earthquake at Qa'en

The Timurid Friday Mosque (Masjed Jame') of Qa'en, capital city of ancient Qohestan province (Wilber, 1955; Tabandeh, 1969; Naderi, 1980; Golombek and Wilber, 1988) (Fig. 6) was built in AD 1368 on the site of a Seljuq (c. AD 1000–1218) mosque that collapsed during an earthquake (Naderi, 1980). The mosque, which was restored in AD 1393, AD 1675, and AD 1847 (buttresses added), experienced intensities of VI (MMI) during the 1968.08.31 (M_s 7.4) Dasht-e-Bayaz earthquake, after which the buttresses were replaced by a concrete reinforcement. The mosque was again damaged (intensity VII) during the Vandik, north Qa'en, earthquake of 1976.11.07

Table 4
Summary of archaeological, architectural, and earthquake information of the Qa'en Jame' (Friday) Mosque site (see Fig. 6)

Structure	Earthquakes (M_s, I_o)	Causative fault	Cultural event/eq. effect at Qa'en
	1997.06.25 (5.8)	Pavak	
	1997.05.10 (7.3, IX +)	Abiz	V (MMI) at Qa'en
	1979.11.27 (7.0, IX)	Dasht-e-Bayaz (E)	V at Qa'en
	1979.01.16 (6.7, VIII +)	Boznabad	IV at Qa'en
	1976.11.07 (6.5, VIII)	Avash	Severely Damaged the Timurid Mosque (VII at Qa'en)
	1968.08.31 (7.4, IX +)	Dasht-e-Bayaz (W)	V (MMI) at Qa'en (pop. 7,000) 1956 Pop. 4,414
	1923.11.29 (5.6, VII)	Pavak?	Destroyed villages SE Qa'en
	1847	?	Damaged the Timurid Mosque; Mosque was restored
	Winter 1675 (6.5)	?	Damaged the Timurid Mosque. The Mosque restored after earthquake
	1549.02.15 (6.7, VIII +)	North Birjand	Five villages destroyed, 3,000 killed in the Birjand region; Qa'en was not damaged
1405–1447: old town/new town	—	—	Shahrokh Mirza replaced the older town which he is said to have destroyed 1393:Timurid Mosque restored
Timurid (1368) Friday Mosque	—	—	Built on the Seljuq Friday Mosque in AD 1368
1225: Yaqut describes as an old town with ancient castle known as No'man-e-Kabir. He does not mention the Mosque	—	—	
	May 1066 (>6.5, >VIII +)	**Pavak/Boznabad?**	**Completely destroyed the Seljuq Mosque (>VIII at Qa'en)**
1052: Nasser Khosrow visited the Seljuq Mosque	—	—	
Seljuq Friday Mosque (~1000)	—	—	Built on the Sassanian Fire Temple (~1000)
978: ebn Hauqal refers to the Friday Mosque	—	—	
?	?		?
Sassanian (224–642) Fire Temple	—	—	
Second century BC: old Arian town of Artacoana	—	—	

(Ms 6.4) (Table 4 and Fig. 6) and experienced an intensity of V (MMI) during the 1997.05.10 (M_w 7.1) Zirkuh earthquake (Berberian et al., 1999; Berberian and Yeats, 1999). The site is located 30 km south of the Dasht-e-Bayaz Fault and 60 km west of the Abiz Fault (Fig. 6).

Archaeological trenching beneath the foundation of the present Timurid Friday Mosque of Qa'en has revealed collapsed walls of the Seljuq Friday Mosque over broken and upside-down Seljuq pottery containing watermelon seeds and a few apricot pits, possibly indicating that collapse took place in the summer, as the result of an earthquake during the Seljuq dynasty (c. AD 1000–1218) (Naderi, 1980; B. Naderi, personal communication, 1991) (Fig. 6 and Table 4). Based on ebn al-Jauzi (1181), ebn al-Athir (1231), al-Dhahabi (1315), and al-Suyuti (1499): "there was a series of earthquake shocks in the Qohestan Province of southern Khorasan which continued for few days in Jumada-II, 458 [May 1066]. In the Qohestan District (Fig. 6), mountains were split, and a number of villages were totally destroyed by landslides. Many people perished, and the survivors remained out in the open" (ebn al-Jauzi, 1181).

There are no precise indications as to where the shocks occurred, and later accounts tend to confuse the issue (Ambraseys and Melville, 1977, 1982; Berberian, 1995a). However, archaeological excavations at the foundation of the Qa'en Friday Mosque indicate that destruction of the Seljuq (c. AD 1000–1218) structure could have happened at the time of the reported historical earthquake in May 1066 (Table 4). Nasser Khosrow (1052) visited the Qa'en Seljuq

Mosque, then known as the 'Great Mosque', 14 years before the earthquake and described it as "the largest arch to be seen in all Khorasan province". Therefore, the Seljuq Mosque was in good condition at least until AD 1052.

Although this destruction, documented by the archaeological evidence and written documents, is clearly related to an earthquake, it is not certain which of the active faults near Qa'en was the source of the earthquake (see Berberian et al., 1999; Berberian and Yeats, 1999) (Fig. 6). However, the complete destruction of the Seljuq Mosque suggests that the earthquake source was close to the city, thus rejecting the Dasht-e-Bayaz and Abiz faults as possible sources (Fig. 6). The Avash left-lateral strike-slip fault, in the mountains approximately 9 km north of Qa'en, the Pavak/Boznabad right-lateral strike-slip fault, located 20 km east of Qa'en, and the southeastern segment of the Ferdows reverse fault, located 26 km southwest of Qa'en, are candidate sources for the May 1066 event (Fig. 6). The Avash Fault, 25 km long, seems to be too short for such a large-magnitude earthquake. In this case the Pavak/Boznabad fault system, with 'Kuh-e-Shekasteh Barqu' [lit. the 'Barqu Broken/Faulted Mountain'] on its eastern side, being 6 km closer to Qa'en than the Ferdows Fault, is a more suitable candidate fault for the AD 1066 earthquake (Fig. 6). The Ferdows Friday Mosque (AD 1200) and the Soltan Mohammad 'Abed Mausoleum of Kakhk (AD 1553) post-date the 1066 event, and the effect of this earthquake on these towns is therefore not known.

6.2. Post-AD 1066 earthquakes

Apparently, an earthquake in AD 1238 damaged Gonabad (83 km NW of Qa'en); however, the Gonabad Seljuq Jame' Mosque (built in AD 1212) presumably escaped destruction (Tabandeh, 1969). Due to uncritical use of second-hand sources, this event was confused with the May 1066 event of Qa'en in figure 5 of Berberian and Yeats (1999). Re-examination of the original texts shows no indication that the AD 1238 event affected Qa'en (Fig. 6).

According to Khandmir (1550), Rumlu (1577), and Qomi (1591) "An earthquake on 1549.02.15 destroyed five villages at Bozhd, Birjand, Siojan, Taqab, and Shahzileh [Fig. 6 shows the approximate meizoseismal area]. All houses were destroyed, and nobody escaped the earthquake. The shock was weaker at Khosf (35 km west of Birjand), and the death toll was estimated between 2000 to 3000 people. The earthquake did not damage Qa'en" (Khandmir, 1550). The North Birjand Fault seems to be the source of this event (Fig. 6).

The winter AD 1675 earthquake allegedly ruined Gonabad with major loss of life, although the Gonabad Jame' Mosque withstood the shock (Tabandeh, 1969). The Gonabad or the Bidokht faults (with fresh displacements visible on aerial photograph nos. 29305 and 29307, World-wide Aerial Surveys, Inc., project 158) are possible sources of the AD 1675 and/or AD 1238 earthquakes (Fig. 6). No evidence of the earthquake is reported from Qa'en. An inscription in Qa'en Mosque records only restoration work in AD 1675, with no reference to any earthquakes. It is important to note that the two Gonabad earthquakes of AD 1238 and AD 1675, reported by Tabandeh (1969), were based on local tradition and require confirmation.

An earthquake in AD 1847 cracked the rear wall of the Qa'en Timurid Friday Mosque, and it became necessary to prop it up with buttresses (Smith, 1876). The source of this event is also unknown.

Finally, an earthquake in 1923.11.29 (M 5.6) was reported to have caused widespread damage in the area SE of Qa'en (exact location unknown). Many houses were ruined, but there were no casualties (Stratil-Sauer, 1950; Ambraseys and Melville, 1977). International Seismological Summary places the epicenter of this event near Zabol, 338 km SE of Qa'en.

The Timurid (1368) Friday Mosque of Qa'en is still standing, suggesting that Qa'en did not suffer severe damage or destruction during the AD 1549 (Birjand), AD 1675 (Gonabad), and AD 1847 earthquakes (Table 4). Hence, despite several references to historical destruction of Qa'en, the sources of these events were farther from Qa'en than the May AD 1066 event (Fig. 6). Albeit clarifying the confusion on the historical earthquakes in the Qa'en region, and utilizing archaeological evidence for the historically recorded event of 1066, palaeoseismological trench investigations are necessary to clarify the ambiguities associated with the seismic sources of several historical earthquakes in this area.

7. Earthquakes in the capital city of Tehran

The number of archaeological sites and historical monuments close to active faults (Fig. 1) indicates that future studies relating archaeological data to earthquakes are warranted, particularly near Tehran, where one-fifth of the 60 million population of Iran is at risk. For example, the Cheshmeh'Ali mound at Ray, now the southern quarter of metropolitan Tehran, and the Qaytariyeh mound of c. 1200–1000 BC in central east Tehran (Kambakhsh-Fard, 1991) should be investigated (Fig. 7). These sites are close to the North Ray, South Ray, Kahrizak, Parchin, North Tehran, and Mosha active reverse faults (Berberian et al., 1985; Berberian and Yeats, 1999), and the area has been affected by destructive earthquakes in 312–281 BC ($M \sim 7.6$), AD 743 ($M \sim 7.2$), AD 855 ($M \sim 7.1$), AD 864 (>5.3), AD 958 ($M \sim 7.7$), AD 1177 ($M \sim 7.2$), AD 1665 ($M \sim 6.5$), and AD 1830 ($M \sim 7.1$). The Cheshmeh'Ali site (along the North Ray Fault) was suddenly abandoned in the third millennium BC (Schmidt, 1940), was again inhabited at the end of the second millennium BC, and later used by Parthians (312 BC–AD 224) and Sassanids (AD 224–642). (Communications with Renata Holod and Fredrik Hiebert of the University of Pensylvania, Philadelphia, in February 2000 indicated that there are no specific references

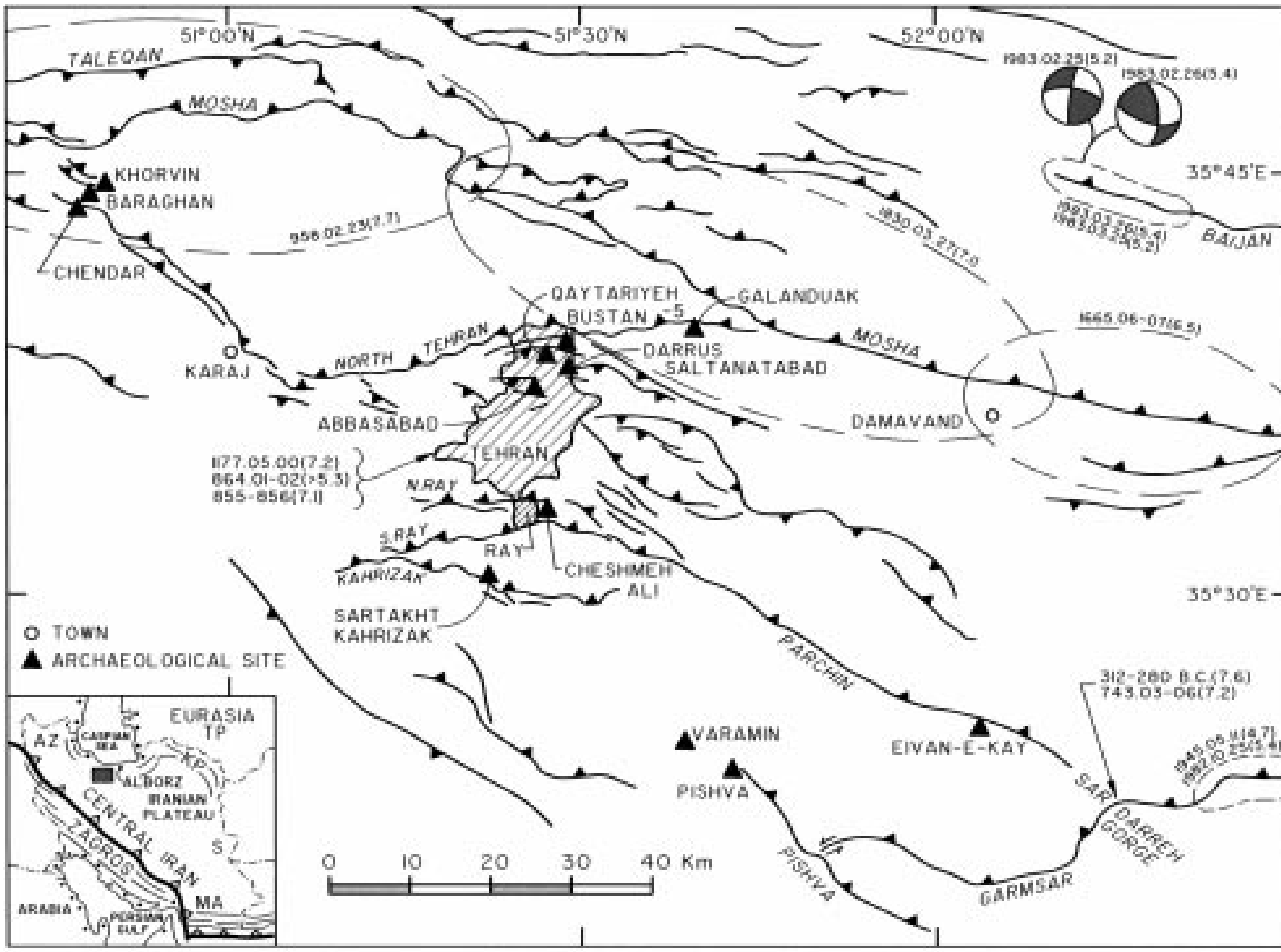

Fig. 7. Fault map (located in Fig. 1) and major archaeological sites (filled triangles) in metropolitan Tehran. Fault symbols are as in Fig. 1. Fault map revised from Berberian et al. (1983, 1985). Meizoseismal areas of large-magnitude historical earthquakes are taken from Berberian and Yeats (1999). Focal mechanisms are from Harvard CMT solutions. For historical earthquakes whose meizoseismal areas are not known, the earthquake dates are given in the vicinity of the destroyed site.

to earthquakes in Eric Schmidt's personal field notes.) The Mil mound (not shown in Fig. 7), a late Sassanid Palace site located east of Cheshmeh'Ali and the Kahrizak reverse fault, does not show any evidence of large-magnitude earthquakes since Sassanid times (M. Kadjar, personal communication, September 1998).

The Qaytariyeh, Darrus, Saltanatabad, Bustan-5, 'Abbasabad, and Galanduak archaeological sites at Tehran, the Kahrizak, Pishva, and Eivan-e-Kay sites at south and southeast of Ray, and the Chendar, Baraghan, and Khorvin sites at Karaj to the west were actively occupied during the period 1200–1000 BC (Fig. 7). All these sites, at least 50 km E–W and 40 km N–S, were suddenly abandoned around 1000–900 BC, never to be occupied again (Kambakhsh-Fard, 1991). The people at the Sartakht Kahrizak mound in south Tehran (Kambakhsh-Fard, 1991) left behind more than 1000 active and in situ pottery kilns on the edge of the hanging wall block of the Kahrizak fault (Fig. 7). This abandonment could possibly be the result of earthquakes. All these archaeological sites were associated with the early Medes and with Raga (Rhages; ancient Ray), one of the great centers in the early first millennium BC. Palaeoseismological trenching across the Kahrizak reverse fault (De Martini et al., 1998) failed to reconstruct the seismic history of the fault and did not resolve the seismic issues discussed here. Archaeological investigations may permit the determination of earthquake recurrence intervals in metropolitan Tehran, which is not possible using historical earthquake data alone (summarized by Berberian and Yeats, 1999).

8. Discussion and conclusions

In the absence of radiometric dating and palaeoseismological trenching in Iran, we have utilized the existing archaeological data to identify large-magnitude earthquakes along faults generating large 20th century AD earthquakes. Clearly, many low- to moderate-magnitude earthquakes generated along the faults are missing from the written historical data as well as the archaeological record. Hence the reported 'maximum intervals' are not directly usable for a detailed seismic hazard assessment. However, the study gives a better understanding of the large-magnitude earthquake activity along individual faults in different seismotectonic provinces of the Iranian Plateau. The proposed maximum return times should be refined by future palaeoseismological trench studies. In this case a correlation between archaeological interpretation and the absolute dates from palaeoseismic trenching would feed back into archaeological investigations in Iran.

The data presented here show a difference between the maximum intervals observed in central and north Iran and those in the Zagros Mountains of southern Iran. The shortest earthquake recurrence interval in Iran discussed in this paper is found along the Dinevar–Nahavand section of the ZMRF, with earthquakes in c. 1650–1600 BC, c. AD 224–459, AD 1008 and 1107, and AD 1957 (M_s 6.7) and 1958 (M_s 6.6) AD, giving area source recurrence intervals of 1800–2100, 500–800, and 850–950 years, respectively (Fig. 2). The recurrence interval separating the oldest earthquakes is twice that for earthquakes during the Christian Era, and there could be a missing earthquake in the first millennium BC. If so, the recurrence interval in this mobile zone near the Arabian platform is less than 1000 years. Available information does not clearly relate the earlier earthquakes to one of the two segments rupturing in AD 1957 and 1958; earlier earthquakes could have ruptured more than one segment or could have continued beyond the 1957 and 1958 rupture zones. Nevertheless, it seems clear that the Dinevar–Nahavand section of the ZMRF was visited by major earthquakes at intervals less than 1000 years long, even though the rupture zones of the earlier earthquakes are still uncertain. Archaeological evidence is not available for the rest of the ZMRF, but the maximum recurrence interval determined in the Dinevar–Nahavand region may apply to other sections of the fault as well.

Iran is highly seismic, but certainly more earthquakes have occurred than have been reported in the written historical source material of AD 800–1900. For example, Mas'udi (943) listed areas famous for frequent great earthquakes, areas visited by Mas'udi himself (see Berberian and Yeats, 1999), including, among others, two towns, Amol and Siraf (Fig. 1), for which no pre-AD 943 recorded documents have survived. The earliest known earthquake in the Amol region (along the south Caspian shore) is the AD 1809 ($M_s \sim 6.5$) event, and in the Siraf port (the present Taheri Port, on the Persian Gulf) the earliest known earthquakes are the 978.06.17 ($M_s > 5.3$) and the AD 1008 Spring ($M_s \sim 6.5$) events. Mas'udi died in AD 956, 22 years before the first recorded Siraf earthquake of 978.06.17. This clearly indicates that the recorded seismic history of Iran is not complete, and there may be missing earthquakes along the ZMRF as well.

An earthquake history as long as that on the ZMRF is found in adjacent Turkmenistan, where the Main Kopeh Dagh strike-slip fault and the related surface and blind thrusts mark the southwestern boundary of the stable Turan (Karakum) Platform. Earthquakes struck the Ashkabad region in c. 2000 BC, the beginning of the Christian Era, and AD 1948 (M_s 7.2), a 'maximum recurrence interval' of about 2000 years (Fig. 5). The Main Kopeh Dagh Fault and the related thrusts extend northwest toward the Caspian Sea, but archaeological evidence is not available to work out the earthquake history of the Main Kopeh Dagh Fault northwest of Ashkabad.

Within the long-settled Central Iranian Plateau, the Ipak Fault (Fig. 3) possibly ruptured in c. 2000–1500 BC and again in AD 1962 (M_s 7.2), a maximum recurrence interval of c. 3500–4000 years. No other candidate fault has been mapped in this area, so this can be considered as the recurrence interval for the Ipak Fault. The Rudbar–Tarom area (Fig. 4) possibly ruptured near the beginning of the first millennium BC and again in AD 1990 (M_w 7.3), a maximum recurrence interval of c. 3000 years. Although the 1990 rupture was on a strike-slip fault, the Manjil active reverse fault could have ruptured in the earlier earthquake. Because there is more than one candidate fault, the recurrence interval is for an area rather than a specific fault. Genuine quiescence of at least 1100 and 1000 years prior to the 1978.09.16 (7.4) Tabas-e-Golshan earthquake, and the 1930.05.06 (7.2) Salmas earthquake, along the Tabas and the Salmas faults, respectively (located in Fig. 1), are already well recorded by archaeological studies within the Central Iranian Plateau (Tchalenko and Berberian, 1974; Berberian, 1979, 1981, 1995a). Elapsed times of 1144 and 948 years after the 856.12.22 ($M \sim 7.9$) Kumes (along the Damghan/Astaneh fault) and the 1052.06.02 ($M \sim 7.0$) Beihaq (Sabzevar) earthquakes (along the Sabzevar thrust), respectively, are already documented by survival of several archaeological monuments in Central Iran (Berberian, 1979, 1981, 1995a).

The Qa'en/Dasht-e-Bayaz region in the Khorasan province of eastern Iran was subjected to a sequence of earthquakes in the period AD 1936–1997, producing surface rupture on left-lateral and right-lateral strike-slip faults (Fig. 6). A large mosque at Qa'en was destroyed by an earthquake, possibly the historical earthquake of AD 1066, with intensities larger than those experienced at Qa'en in any of the 20th century AD earthquakes, including a nearby earthquake in 1976 (M_s 6.4; Fig. 6 and Table 4). The difference in intensities rules out the Dasht-e-Bayaz or Abiz faults as sources for the AD 1066 earthquake (Table 4), but several active faults near Qa'en are potential candidate faults (Fig. 6). Accordingly, the 900-year recurrence interval is for an area source, with the additional constraint that the fault that ruptured in AD 1066 may not have ruptured in the 20th century. Berberian and Yeats (1999) suggested that the Dasht-e-Bayaz Fault has a minimum slip rate of 2.5 mm/year based on a comparison of AD 1968 offsets with displacements of ancient underground canals ('qanats') (cf. Ambraseys and Tchalenko, 1969).

The 250-cm left-lateral strike-slip released in 1968 could have accumulated in about 1000 years with this slip rate. However, the Dasht-e-Bayaz Fault was probably not the source of the 1066 earthquake at Qa'en, since the 1968 (M_s 7.4) event had an intensity of V (MMI) at Qa'en in the south and VI (MMI) at Gonabad in the north (Fig. 6).

The Qa'en earthquake of AD 1066 appears to be a single earthquake, whereas the 20th century AD earthquake sequence at the Qa'en/Dasht-e-Bayaz region included several earthquakes with $M > 7.0$ (Fig. 6). This may indicate that the region does not necessarily act as it did in the 20th century, but is capable of sustaining a single earthquake not followed by others. Therefore, although one earthquake may trigger another soon after, it does not always do so.

The archaeology-based recurrence intervals discussed in this paper are longer in the Central Iranian Plateau than they are in the Zagros belt near the plateau margin. Historical evidence from other areas, summarized in Berberian and Yeats (1999), places some constraints on recurrence intervals in other parts of Iran, but these constraints are not long enough to add information to this conclusion. The long-term seismicity of central and north Iran is clearly different from that of the Zagros in that a few thousand years of historical earthquake records are not long enough to record a complete seismic cycle, whereas a few hundred years is more than adequate in the Zagros (e.g. the AD 1440 and the AD 1972 earthquakes at Qir, the AD 1593 and the AD 1960 earthquakes at Lar, and the AD 1666 and the AD 1977 earthquakes at Ardal; see Berberian, 1995b). Higher deformation rates and shorter recurrence intervals in the Zagros Mountains are consistent with the high rate of diffuse seismicity, high uplift rates of 1.0–6.6 mm/year (Vita-Finzi, 1978, 1979; C. Vita-Finzi, personal communication, 26 October 1998), and a higher velocity field in the Zagros (Jackson et al., 1995), where a $\sim$20 mm/year local shortening rate is estimated (Jackson and McKenzie, 1984, 1988).

The present study draws attention to the value of archaeological evidence in seismic studies. Similar systematic approaches have been made in different parts of the Iranian Plateau; more than 250,000 archaeological sites have the potential for recording earthquakes. This provides opportunities to: (i) obtain and interpret information on large-magnitude prehistoric earthquakes occurring over several seismic cycles by extending the existing seismic window back in time, (ii) understand earthquake fault behavior through time, (iii) direct future palaeoseismological trench studies, and (iv) initiate new archaeoseismic investigations amongst archaeologists and earth scientists working in Iran.

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